AMENDMENT TO THE SPECIFICATION

Please amend the entire specification. A substitute specification is attached to this Amendment as APPENDIX I.

<u>APPENDIX I</u>

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APPLICATION

for

UNITED STATES LETTERS PATENT

by

LANG LIU

on the invention entitled

A METHOD AND APPARATUS FOR ANALYZING CONTOUR OF THREE DIMENSIONAL OBJECT SURFACE APPLYING PROJECTED MOIRE FRINGE INTERFEROMETRY

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A METHOD AND APPARATUS FOR ANALYZING CONTOUR OF THREE DIMENSIONAL OBJECT SURFACE APPLYING PROJECTED MOIRE FRINGE INTERFEROMETRY

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BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is related to a method and apparatus for three dimensional (3D)

10 surface measurement, and more particularly related to a method and apparatus for analyzing

absolute contour of full fielded 3D surface of objects applying a projected moire fringe

interferometry.

2. Description of the Prior Art

15 Measuring contour of three dimensional surface of objects attracts attention in the society

of engineering and technology. The currently available commercial apparatus for 3D

surface measurement includes a type of instrument for measuring three-coordinate data of

objects which is relied on mechanically contacting each point of the object surface, and

another type of laser instrument of measuring three-coordinate data of objects. The

20 instrument for the contacting measurement is equipped with a mechanical probe. The probe

which is driven by a numerical control mechanism travels on the surface of an object under

measurement to thereby provide the three-coordinate data for every point of the object

surface. Accuracy of the spatial measurement is generally better than 0.01 mm for the

instrument. However, a measuring speed of the instrument is relatively slow, since it takes

25 times for the numerical system to move across the surface while the mechanical probe applies

forces at certain extent to the object.

In stead of applying the mechanical probe, the laser instrument employs an optical probe which is driven by a numerical control system. An optical spot generated by the optical probe scans surface of an object. In general, the laser instrument improves the measuring speed while suffering a loss of some degree of the accuracy in the spatial measurement.

5   However, increase of the measuring speed for the laser instrument is still limited by the moving speed of the numerical control system. Therefore, a full field measurement of the object will be optimum if it can largely increase the measuring speed.

A moire image including moire fringes is obtained from applying a projected moire

10   interferometry. The fringes are produced from interfering an optical image of a master grating, when the image is optically positioned on a submaster grating. The projected moire interferometry is a full field non-contacting technique for measurement of characteristics of the object surface, which possesses a plurality of measuring capabilities as compared with a holographic interferometry. However, it is more important that, the projected moire

15   interferometry enables controlling its sensitivity in measurement so that the moire interferometry is excellent to reject external interference. For this reason, there is a great prospect of utilizing the projected moire interferometry in engineering applications.

A moire contouring is a promising optical method for imaging object surface, which is

20   originally introduced by Takasaki and Meadows et. al. An apparatus which applies the method is actually quite simple, including a grating which is positioned adjacent an object so that shadow fringes can be observed on the object after projecting lights through the grating. The shadow fringes are equivalent to lines of the moire contouring under certain conditions, which can be used to measure surface characteristics of objects. The method is particularly

25   useful to measure objects having small sizes since the grating size limits application of the apparatus only to the small objects.

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Another method of the moire contouring is respectively introduced by Benoit, P.;

Yoshino, Y.; Suzuki, M. and others.   The method includes projecting an image of grooves of

a master grating onto the surface of an object to thereby image a graph of the moire contour

of the object through a submaster grating.   The method is referred to the projected moire

5   interferometry, which is particularly useful to measure objects having large sizes.   Under

certain conditions, beat fringes generated from a combining effect of the master grating and

submaster grating provide lines of a contour map of the imaged object surface, which is

analogous to the way a topographic map delineates the contour of the land.   In the early

1980s, image processing was successfully introduced for analyzing the moire fringes.   Core

10   technologies of the image processing particularly include a phase shift algorithm and

unwrapping algorithm, which makes the projected moire fringe interferometry enable to

perform a real-time measurement.

According to studies of Meadows, Takasak and Suzuki et. al, the moire fringes become

15   the respective lines of the surface contour map for an object if following criteria are met:

optical centers of the respective projection and imagining optical axe are in parallel; spaces of

the respective projecting master grating and imaging submaster grating are the same; focal

lengths of the respective projection lens and imaging lens are the same; and distance between

the projection grating and lens is the same as compared with distance between the imaging

20   grating and lens.

Referring to Figure 1, there is illustrated a prior art moire interferometer, wherein a light

source **1** projects light rays which pass through a projection master grating **2**, so that an image

of grooves of the master grating is focused on an object **4** under measurement after the lights

25   optically pass through a projection lens **3** .   An image of the measured object is then

positioned on a submaster grating **6** in addition to moire fringes which are also formed.

Images of the formed moire fringes are then optically recorded by a camera **8** through a camera lens **7**.

However, there are two unresolved problems which have persistently associated with the projected moire interferometry long time ago. The first one is that contour lines of the contour map for the object surface, which are described by the moire fringes, are function of orders of the fringes. Therefore, differences in attitude are not equal for respective two adjacent contour lines of the map. In fact, the attitude difference is also a function of the fringe order. Therefore, it is necessary to accurately determine the absolute orders of the moire fringes if absolute appearance of the 3D object surface is desired. The second problem is a necessity of accurately measuring object distances between the respective projection device to the object, and the imaging device to the object, and imaging distances between the respective projection grating to the object, and the image grating to the object. The currently available projected moire interferometer is unable to accurately measure the above mentioned distances. In stead, it is from a rough measurement to estimate the object distances and image distances, according to an assumption that the attitude differences between the respective two adjacent contour lines are constant.

SUMMARY OF THE INVENTION

Purpose of the Invention

It is therefore an objective of the present invention to provide a method and apparatus

5   from an improved projected moire fringe interferometry which overcomes the problems of

the currently available techniques for measuring surface contour.   The present invention

method and apparatus can measure the absolute contour of the object surface with high

accuracies in combination with advantage of the real-time analysis from the prior projected

moire interferometry.

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Contents of the Invention

The techniques which are applied to realize the objective of the present invention include

an apparatus for measuring contour of the 3D surface of objects.   The apparatus is

comprised of a projection device including a mark point and master grating, an imaging

15   device including a mark point and submaster grating, and a first and second rectilinearly

movable axles aligning with the respective x and y axe of the x-y coordinate system.

Application of the rectilinearly movable coordinate axles can construct a right angled triangle

from using the mark point of the projection device, the mark point of the imaging device, and

an image of the mark point of the projection device which is projected to an exterior surface

20   of the object, wherein they are at an arbitrary positions where an image of the object can be

formed.

The first rectilinearly movable axle having a first grating ruler is aligned with an optical

axis of the imaging device, which is positioned perpendicular to the second rectilinearly

25   movable axle having a second grating ruler.   In addition, an optical axis of the projection

device intersects the second rectilinearly movable axle at an angle γ.   The optical axe of the respective projection device and imaging device intersects each other at an angle θ, wherein the angles γ and θ are complementary.

5   The present invention of the measurement apparatus also includes an image capture board to digitize image signals and a computer to process the digitized images.

The projection device from the present invention includes a light source, a master grating, a mark point, and a movable projection lens, wherein the mark point can be positioned behind 10   the master grating, or in parallel with the master grating.

The imaging device from the present invention includes a light path for measuring purpose, wherein optical components which are positioned within the light path include a camera, a submaster grating, a mark point which can be switched in and off the light path, 15   and a movable imaging lens, wherein the mark point is positioned in parallel with the submaster grating.

In addition, the imaging device form the present invention can also have another preferred embodiment including a light path for image in addition to the light path for 20   measurement.   The light path for measurement has optical components including a camera, submaster grating, and a movable imaging lens. The light path for image includes a camera which records an image of a mark point, a reflection mirror which reflects an incident light at an angle of 90 degrees, the mark point, and a square prism which is positioned between the imaging lens and the submaster grating, wherein the prism can split an incident light to two 25   emerging lights, which one emerging light travels along a direction with 90 degrees to another emerging light aligning with the incident light.

The disclosed master and submaster gratings of the respective projection and imaging devices from the present invention can be a type of the Ronchi grating or sinusoidal grating. The mark points have the shape of a circle or cross.

5   The light which is employed in the present invention includes a white light.

The illustrated movable projection lens which is positioned inside of the projection device includes a linear positioner which can move the lens.   Similarly, the illustrated movable imaging lens which is positioned inside of the imaging device includes a linear
10   positioner for moving the lens.

The present invention includes the method of measuring contour of the 3D object surface, wherein the method is comprised of the stops of:

(1) establishing a right angled triangle from connecting the mark point of the projection
15   device, the mark point of the imaging device, and the image of the mark point of the projection device which is projected onto the object surface;

(2) determining a conjugated projecting distance, and a conjugated imaging distance;

(3) calculating a projected object and image distances, and imaged object and image distances;

20   (4) focusing automatically of the respective projection lens and imaging lens in accordance with the calculated projected object and image distances, and the calculated imaged object and image distances to form the moire fringes on the submaster grating of the imaging device;

(5) calculating a phase distribution through the object surface from applying the
25   phase-shift algorithm and unwrapping algorithm in reference of a zero order of the phase which is defined as the image of the mark point which is projected on the object; and

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(6) calculating a height distribution.

Accordingly, the present invention method includes: first establishing the right angled triangle from applying the mark point of the projection device, mark point of the imaging device, and the image of the mark point of the projection device which is projected onto the object surface; measuring the respective projected object and image distances, and the respective imaged object and image distances at a position where an image is formed, wherein the measurement is conducted from using the mark points of the respective projection and imaging devices, and the rectilinearly movable axles which are aligned with the respective x and y coordinate axe; then determining the position of a moire fringe having the zero-order phase according to the image of the mark point of the projection device, which is projected on the surface of the object; deciding orders of the moire fringes positioned in a full field of the object surface from applying the phase-shift algorithm and unwrapping algorithm; and finally calculating an accurate contour of the object 3D surface according to relationships of altitudes of the object surface points and the moire fringes in reference of a point of the object surface which serves as a reference point of the coordinates.

The right angled triangle as illustrated above is established through the following steps: moving the object into a viewable field of the imaging device; focusing an image of the mark point which is projected on the object surface; and aligning the image of the mark point on the object surface with the mark point of the imaging device.

The conjugated projection and imaging distances, which are illustrated above, are determined from the following steps: calculating lengths of the respective two sides of a right angled triangle ΔADE from applying a known length of the rest one side and a known degree of an angle of the triangle, where AE = AD/tg θ; DE = AD/sin θ. The angle θ is between

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the optical axe of the respective projection and imaging devices, which can be calculated from: $\theta = \text{arctg } R_2/R_1$. AD is a distance between the projection and imaging device, which is measured from a reading of the second grating ruler (a length of the second rectilinearly movable axle which forms one side of the right angled triangle ΔADE), R_1 and R_2 are moved distances of the respective master and submaster gratings, AE is an imaged conjugated distance between the object and submaster grating of the imaging device, and DE is a projected conjugated distance between the master grating of the projection device and the object.

Therefore, the projected object and image distances, and the imaged object and image distances can be calculated according the following respective equations:

$$Z_C + Z_{CF} = \frac{AD}{\text{tg}\vartheta} \qquad\qquad \frac{1}{Z_C} + \frac{1}{Z_{CF}} = \frac{1}{F_1}$$

$$L_p + L_{PF} = \frac{AD}{\sin\vartheta} \qquad\qquad \frac{1}{L_p} + \frac{1}{L_{PF}} = \frac{1}{F_2}$$

where, Z_C is the imaged object distance, Z_{CF} is the imaged image distance, L_{PF} is the projected image distance, L_P is the projected object distance, F_1 is the focal length of the imaging device, and F_2 is the focal length of the projection device.

The present invention enables to construct the moire fringes which are positioned on the submaster grating of the imaging device from the step of automatically focusing. The operation of the automatically focusing moves the projection lens and imaging lens to the respective positions so that the moire fringes are formed, wherein the movement is conducted according to the calculated data including the projected object and image distances, and the imaged object and image distances.

Finally, the present invention enables to calculate the height distribution according to the following equations:

$$Z = -\frac{(\frac{\varphi}{2\pi f} + X_C)D - L_{PF}B}{(\frac{\varphi}{2\pi f} + X_C)C - L_{PF}A}$$

$$X_Z = \frac{Z + Z_C}{Z_{CF}} X_C$$

$$Y_Z = \frac{Z + Z_C}{Z_{CF}} Y_C$$

where X_Z, Y_Z, and Z are the respective coordinates for a point of the object surface which is spatially positioned, f is a grating frequency, and ϕ is a phase.

$$A = Z_C Z_{CF} \sin\theta + Z_C X_C \cos\theta \qquad B = Z_C^2 X_C \cos\theta$$

$$C = Z_C Z_{CF} \cos\theta - Z_C X_C \sin\theta \qquad D = -Z_C^2 X_C \sin\theta + Z_C Z_{CF} L_P$$

The following is a detailed disclosure of the present invention apparatus and method taken in conjunction with the drawings and examples.   However, referring particularly to the examples is for the purpose of illustration only and not limitation of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring particularly to the drawings for the purpose of illustration only and not limitation, there is illustrated:

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FIG. 1 is a schematic diagram of main structural elements for a prior art of the moire interferometry;

FIG. 2 is a diagrammatic representation of the present invention apparatus for measuring

10 contour of a full field three dimensional surface of an object by applying the moire fringes;

FIG. 3 is a schematic diagram which illustrates optical components for a preferred embodiment of a projection device of the present invention apparatus;

15 FIG. 4 is a schematic diagram which illustrates optical components for a preferred embodiment of an imaging device from the present invention apparatus;

FIG. 5 is a schematic diagram, which illustrates relationship of calculated parameters from the present invention;

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FIG. 6 is a schematic diagram to illustrate principles which are used in measurement of appearance of the object applying the moire fringes;

FIG. 7 is a flow chart which illustrates steps of the present invention method for

25 measuring contour of a full field three dimensional surface of an object by applying the moire fringes;

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FIG. 8 is a schematic diagram which illustrates optical components from another embodiment of the projection device of the present invention apparatus; and

5   FIG. 9 is a schematic diagram which illustrates optical components from another embodiment of the imaging device of the present invention apparatus.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Although specific embodiments of the present invention will now be described with reference to the drawings, it should be understood that such embodiments are by way of

5   example only and merely illustrative of but a small number of the many possible specific embodiments which can represent applications of the principles of the present invention. Various changes and modifications obvious to one skilled in the art to which the present invention pertains are deemed to be within the spirit, scope and contemplation of the present invention as further defined in the appended claims.

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Referring to Figure 2, there is illustrated structural components of the present invention apparatus for measuring contour of a full field three dimensional surface of an object by applying projected moire fringe interferometry.   The apparatus is comprised of an imaging device **20**, a first rectilinearly movable axle **40** and a first grating ruler **60** which are

15   positioned to align with an optical axis of the imaging device **20**, and an object **80** positioned on a rotating objective receiving support **30** which is rotatably affixed to a movable plate **41**, wherein the movable plate **41** is slidably connected to the first rectilinearly movable axle **40**.

The apparatus further includes a second rectilinearly movable axle **50** and a second

20   grating ruler **70** which are positioned to perpendicular to the first rectilinearly movable axle **40**, a projection device **10** which is positioned on the second rectilinearly movable axle **50** and whose optical axis intersects the axle **50** at an angle γ, and a marble platform **90** which affixes including the first rectilinearly movable axle **40** and the first grating ruler **60**, the second rectilinearly movable axle **50** and the second grating ruler **70**, and the imaging device

25   **20**.   In addition, the present invention apparatus additionally includes an image capture

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board **100** which is used to digitize image signals, and a computer **110** for processing the digitized image signals.

As illustrated in Figure 3, the projection device **10** is comprised of optical components including a light source **11** which is positioned in front of a condenser **12**, a master grating **13** whose grooves are positioned on one surface of the grating, a mark point **14** which is positioned on the opposite surface of the grating, and a projection lens **15**.   The master grating **13** is movable aligning with an orientation of the grating surface, wherein the movement of the grating **13** is controlled by a linear positioner **17**.   Similarly, the projection lens **15** is movable aligning with an optical axis of the projection device, wherein the movement of the lens **15** is controlled by a linear positioner **16**.

It will be appreciated that, as illustrated the projection device **10** in Figure 8, the mark point **14** can be positioned in parallel with the grooves of the master grating **13**.

The imaging device **20** is comprised of a measuring light path, which includes a camera **21**, a switcher **27** for switching a mark point **25** positioned and the submaster grating **23**, and a movable imaging lens **29**

Referring to Figure 9, the measuring light path includes a camera **21** having a camera lens **22** which records images of the moire fringes positioned on the submaster grating, the switcher **27** which can switch the mark point **25** and the submaster grating **23** respectively in or off the optical axis of the imaging device, and the movable imaging lens **29** whose movement aligning with the optical axis is controlled by a linear positioner **29A**.

It will be appreciated that, as illustrated in Figure 4, the imaging device **20** includes an

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alternative embodiment comprising a measuring light path **120** and imaging light path **130**. The imaging optical path **130** includes the movable imaging lens **29**, the linear positioner **29A** which controls the movement of the movable imaging lens **29** aligning with an optical axis of the lens **29**, a square prism **24** which is positioned between the image lens **29** and

5 submaster grating **23** for splitting an incident light into a first and second emerging lights, wherein the first emerging light is aligned with the incident light and the second emerging light is departing from the first emerging light at an angle of 90 degrees, a mark point **25** which is positioned between the square prism **24** and a reflection mirror **26**, wherein the mirror **26** reflects the second emerging light at an angle of 90 degrees, an imaging camera **28**

10 having a camera lens **27** for recording the imaged mark point **25**. The measuring optical path **120** includes the movable image lens **29**, the linear positioner **29A** which controls movement of the lens **29** along its optical axis, the measuring camera **21** having the camera lens **22** for receiving images of the moire fringes positioned on the submaster grating **23**.

15 Referring now to Figure 7, there is illustrated a flow chart of the present invention method to measure contour of a full field 3D surface of an object. During the measurement, first move the measured object **80** along the first rectilinearly movable axle **40** to a position mostly adjacent the imaging device **20**. Then focus the projection lens of the projection device **10** to thereby form a clear image of the mark point of the projection device onto the

20 surface of the measured object **80**. Focus the imaging lens of the image device **20** to thereby form a clear image of the object **80** including the imaged mark point on the object. Additionally move the projection device **10** along the second rectilinearly movable axle **50** to thereby superpose the image of the imaged mark point which is projected onto the object surface upon the mark point of the imaging device **20**. In this setting, a triangle $\triangle ABC$ as

25 illustrated in Figure 5 is formed by connecting the mark point of the projection device, the mark point of the imaging device, and the image of the mark point of the projection device on

the object surface.   In addition, the triangle $\triangle ABC$ is a right angled one, since the first

rectilinearly movable axle **40** crosses the second rectilinearly movable axle **50**, and a line AB

which connects the mark point of the projection device to the mark point of the imaging

device is aligned with the moving direction of the second rectilinearly movable axle **50**.

5   Therefore, the first step includes measuring a length of the right-angled side AB, and an angle

θ when the optical axis of the projection device **10** intersects the optical axis of the imaging

device **20**.

Then reset the first and second grating ruler **60** and **70** to a respective zero reading.

10   Move the object **80** to a position E along the first rectilinearly movable axle **40**, which results

in a reading of a moved distance as R_1 on the first grating ruler **60**.   Move the projection

device **10** to a position D along the second rectilinearly movable axle **50**, which results in a

reading of a moved distance as R_2 on the second grating ruler **70**.   In this setting, a new right

angled triangle $\triangle ADE$ is constructed from connecting the mark point **15** of the projection

15   device, the mark point **25** of the imaging device, and the reference point E on the object.   If

defining a focal length of the movable imaging lens **29** as F_1, an imaged object distance as Z_C,

an imaged image distance as Z_{CF}, a focal length of the movable projection lens **15** as F_2, a

projected object distance as L_P, and a projected image distance L_{PF}, then the following

20   equations can be given:

$$AD = AB + R_2 \tag{1}$$

$$\frac{1}{Z_C} + \frac{1}{Z_{CF}} = \frac{1}{F_1} \tag{2}$$

$$Z_C + Z_{CF} = \frac{AD}{tg\vartheta} \tag{3}$$

$$L_p + L_{PF} = \frac{AD}{\sin\vartheta} \tag{4}$$

$$\frac{1}{L_P} + \frac{1}{L_{PF}} = \frac{1}{2F_2} \tag{5}$$

Therefore, determine values of the respective Z_C and Z_{CP} according to Equations (2) and (3), and calculate values of the respective L_P and L_{PF} according to Equations (4) and (5). Then perform automatically focusing operation for the movable projection lens and image lens.

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The automatically focusing operation includes moving the movable projection lens **15** of the projection device **10** to a position which correlates to the projected image distance L_{PF}. This movement results in forming a clear image of grooves of the master grating onto the object surface after light rays radiated from the light source pass through the master grating to the object. Then move the imaging lens of the imaging device to a position which correlates to the imaged image distance Z_{CF}. The movement results in forming interference fringes on the submaster grating **23**, which are the moire fringes, in addition to an image of the object surface having the groove image of the master grating which is projected onto the object surface.

15

Then, the moire fringes are recorded by the imaging camera, which are further transferred to the image capture board **100** for digitization. The digitized images of the moire fringes are further processed in the computer **110** so that a first graph of the digitized more fringes can be obtained.

20

For obtaining additional three graphs of the moiré fringes, move the master grating of the projection device in the direction which is vertical to the optical axis of the projection device according to a moving distance of a respective quarter, half and three-quarter grating space. Therefore, a total of four graphs of the moire fringes can be obtained, which are then recorded by the camera. The graphs are further input into the computer **110** through the image capture board **100**. Then apply the phase-shift algorithm to obtain a phase diagram

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in the phase ranging from 0 to 2π. The algorithm includes the following equations:

$$I_1 = I_0 + A\sin(\varphi + 0) \qquad (6)$$

$$I_2 = I_0 + A\sin(\varphi + \pi\frac{1}{2}) \qquad (7)$$

$$I_3 = I_0 + A\sin(\varphi + \pi) \qquad (8)$$

$$I_4 = I_0 + A\sin(\varphi + \frac{3\pi}{2}) \qquad (9)$$

$$\varphi = tg^{-1}\frac{I_4 - I_2}{I_1 - I_3} \qquad (10)$$

10   where I_0 is an intensity of the background lights, A is a contrast of the fringes; and ω is a

phase of the measured point.

Then, calculate the phase data of the phase diagram applying the unwrapping algorithm

having principles as:

15    $\varphi_2 = \varphi_1 - 2\pi$ if $\varphi_2 - \varphi_1 \geq \pi$, and $\varphi_2 = \varphi_1 + 2\pi$ if $\varphi_2 - \varphi_1 \leq -\pi$

This forms a continuously phase distribution.

The next step of the present invention method is to calculate a high distribution of the

20   object from applying the respective derived projected moire heights and the phase equations

in accordance with the following parameters which are known: the imaged object distance Z_C,

imaged image distance Z_{CF}, projected image distance, projected object distance L_P,

intersected angle θ between the optical axe of the respective projection and imaging devices,

and the grating space $P_P = P_C = P$.

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In addition, the equations are versatile, which correlates a random triangle established

from connecting centers of the respective master and submaster gratings to the image of the

master grating which is projected on the object surface.

As illustrated in Figure 6, a coordinate system is established on a plane defined by the projection grating, reference plane (where a surface point of the object is positioned) and reference grating (which is the submaster grating). In addition to define the projection grating space as P_P (or the spatial frequency f_P) and the reference grating space as P_C (or the spatial frequency f_C), an equation for the projection grating is:

$$I_P = \sin(2\pi f_P X_P) \quad (11)$$

(assuming an initial phase to be zero, in addition, if non-sinusoidal functions are used in the equation of the projection grating, they can be converted into a combination of series of sinusoidal functions through the Fourier transformation. However, the first term of the Fourier series must be obtained so that the phase can be analyzed).

If X is correlated to X_P on the reference plane, therefore

$$tg\alpha = \frac{X_P}{L_{PF}} \quad (12)$$

$$\frac{X}{\sin\alpha} = \frac{L_P}{\sin(\frac{\pi}{2} - \theta + \alpha)} = \frac{L_P}{\cos\theta\cos\alpha + \sin\theta\sin\alpha} \quad (13)$$

which is, $X = \dfrac{L_P}{\cos\theta ctg\alpha + \sin\theta};$

Accordingly, Equation 14 can be obtained from Equations (12) and (13):

$$X_P = \frac{XL_{PF}\cos\theta}{L_P - X\sin\theta} \quad (14)$$

From the equations listed above, it is clear that there is a non-lineal relationship between X_P and X, which leads to occurrence of distortion of the imaged grating which is projected on the reference plane. Therefore, the imaged grating will not be equal-spaced any more. An equation therefore can be expressed as follows for the imaged grating on the reference plane:

$$I = I_P = \sin(2\pi f_P \frac{XL_{PF}\cos\theta}{L_P - X\sin\theta}) \quad (15)$$

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If now considering the imaging system, an image of the projected grating is formed on the plane where the reference grating is located.

Referring to Figure 6, it can find that $\dfrac{X}{Z_C} = \dfrac{X_C}{Z_{CF}}$ (16) so that: $X = \dfrac{Z_C}{Z_{CF}} X_C$ (17).

5   Combining Equation (17) with Equation (15), an Equation (18) of the light intensity distribution can be obtained for the projected grating image which is formed at the reference grating plane:

$$I_C = \sin(2\pi f_P \frac{X_C Z_C L_{PF} \cos\theta}{Z_{CF} L_P - Z_C X_C \sin\theta}) \qquad (18)$$

10   If an equation for the reference grating is $I_{CR} = \sin(2\pi f_C X_C + \Delta)$ (19), then an Equation (20) for the mixed light intensity of the moire fringes formed by I_C and I_{CR} can be expressed as follows:

$$\begin{aligned}
I_{CCD} = I_C \times I_{CR} &= \sin(2\pi f_P \frac{X_C Z_C L_{PF} \cos\theta}{Z_{CF} L_P - Z_C X_C \sin\theta}) \times \sin(2\pi f_C X_C + \Delta) \\
&= \frac{1}{2}\left\{\cos\left[2\pi f_P \frac{X_C Z_C L_{PF} \cos\theta}{Z_{CF} L_P - Z_C X_C \sin\theta} - (2\pi f_C X_C + \Delta)\right] - \cos\left[2\pi f_P \frac{X_C Z_C L_{PF} \cos\theta}{Z_{CF} L_P - Z_C X_C \sin\theta} + (2\pi f_C X_C + \Delta)\right]\right\}
\end{aligned}$$

15   (20)

If applying the projected moire fringe interferometry to measure contour of the object surface, it requires that structure of the grating grooves cannot be recognized by a CCD camera according to the respective I_C and I_{CR}.   Thus, the second item of Equation (20) is related to effect of high frequencies, which correlates a uniform optical field so that it cannot

20   be recognized by the CCD camera. However, the CCD camera can only recognize optical fields which correlate to moire fringes with low frequencies that are described in the first item of Equation (20). Therefore, Equation (20) can be simplified as follows:

$$I_{CCD} = \frac{1}{2}\cos\left[2\pi f_P \frac{X_C Z_C L_{PF} \cos\theta}{Z_{CF} L_P - Z_C X_C \sin\theta} - (2\pi f_C X_C + \Delta)\right] \qquad (21)$$

25   where $f_P = f_C = f$ is generally agreed.

If the object is positioned behind the reference plane as illustrated in Figure 6, and a point of the object which is selected serves as a reference point "0" (referring to a zero height of the point), the following Equations (22) and (23) can be obtained:

$$\frac{X'}{Z_C} = \frac{X - X' - \Delta X}{Z} = \frac{X - \Delta X}{Z + Z_C} = \frac{X_Z}{Z + Z_C} \quad (22)$$

$$X' = \frac{Z_C}{Z + Z_C}(X - \Delta X) \quad (23)$$

Referring to geometrical relationships in the Figure 6, it shows: $\dfrac{Z}{\Delta X} = tg(\dfrac{\pi}{2} - \theta + \alpha)$, so that $\Delta X = Z\dfrac{1 - ctg\theta tg\alpha}{ctg\theta + tg\alpha}$ (24). Equation 24 can be derived as:

$$\Delta X = Z\frac{\sin\theta - \cos\theta\, tg\alpha}{\cos\theta + \sin\theta\, tg\alpha} \quad (25).$$

In addition, Equation (13) also can be expressed as: $X = \dfrac{L_P tg\alpha}{\cos\theta + \sin\theta\, tg\alpha}$ (26)

Therefore, a simplified Equation (27) can be obtained by combining Equations (25), (26) and (12) with Equation (23):

$$X_P = L_{PF} \times \frac{X'(Z + Z_C)\cos\theta + ZZ_C\sin\theta}{Z_C L_P + ZZ_C\cos\theta - X'(Z + Z_C)\sin\theta} \quad (27)$$

Further combining $X' = \dfrac{Z_C}{Z_{CF}}X_C$ with Equation (27), an Equation (28) can be obtained:

$$X_P = L_{PF} \times \frac{Z_C X_C(Z + Z_C)\cos\theta + ZZ_C Z_{CF}\sin\theta}{Z_C Z_{CF} L_P + ZZ_C Z_{CF}\cos\theta - Z_C X_C(Z + Z_C)\sin\theta} \quad (28)$$

Light intensity distribution of projected grating image which is formed on the plane of the reference grating can be described as follows after it is modulated by the height attitude Z:

$$I_C = \sin(2\pi f_P \times L_{PF} \times \frac{Z_C X_C (Z + Z_C)\cos\theta + Z Z_C Z_{CF}\sin\theta}{Z_C Z_{CF} L_P + Z Z_C Z_{CF}\cos\theta - Z_C X_C (Z + Z_C)\sin\theta})$$

$$= \sin(2\pi f_P \times L_{PF} \times \frac{Z(Z_C Z_{CF}\sin\theta + Z_C X_C\cos\theta) + Z_C^2 X_C\cos\theta}{Z(Z_C Z_{CF}\cos\theta - Z_C X_C\sin\theta) - Z_C^2 X_C\sin\theta + Z_C Z_{CF} L_P} \qquad (29)$$

In addition, the grating equation can be rewritten as $\quad I_{CR} = \sin(2\pi f_C X_C + \Delta) \qquad (9)$

Then, if considering facts of $\quad I_{CCD} = I_C \times I_{CR} \quad$ and the high frequency grating structure which

cannot be recognized, lead the following Equation (30):

$$I_{CCD} = \frac{1}{2}\cos\left[2\pi f_P L_{PF}\frac{Z(Z_C Z_{CF}\sin\theta + Z_C X_C\cos\theta) + Z_C^2 X_C\cos\theta}{Z(Z_C Z_{CF}\cos\theta - Z_C X_C\sin\theta) - Z_C^2 X_C\sin\theta + Z_C Z_{CF} L_P} - (2\pi f_C X_C + \Delta)\right] \qquad (30)$$

Generally, $f_P = f_c = f$. If $Z = 0$, Equation (30) can be simplified to Equation (21), which also

proves correctness of the above mathematical deduction.

In addition, the phase can be expressed as:

$$\varphi = 2\pi f_P L_{PF}\frac{ZA + B}{ZC + D} - (2\pi f_C X_C + \Delta) \qquad (31)$$

where,

$$A = Z_C Z_{CF}\sin\theta + Z_C X_C\cos\theta \qquad\qquad B = Z_C^2 X_C\cos\theta$$

$$C = Z_C Z_{CF}\cos\theta - Z_C X_C\sin\theta \qquad\qquad D = -Z_C^2 X_C\sin\theta + Z_C Z_{CF} L_P$$

In terms of Equation (31), calculating the phase of the origin of the coordinates:

$X_C = 0$, $Y_C = 0$, $Z = 0$, which are combined with Equation (21) to thereby obtain: $\varphi_0 = -\Delta$.

Here, φ_0 can be eliminated since it is a constant which is added to all the phases.   This

means to treat all the phases as the following operation:

$\varphi = \varphi - \varphi_0 \qquad (31 - 1)$; therefore, a full-field phase can be obtained as:

$$\varphi = 2\pi f_P L_{PF}\frac{ZA + B}{ZC + D} - 2\pi f_C X_C \qquad (32)$$

If applying $f_P = f_C = f$, Z can be expressed as:

$$Z = -\frac{(\frac{\varphi}{2\pi f} + X_C)D - L_{PF}B}{(\frac{\varphi}{2\pi f} + X_C)C - L_{PF}A} \qquad (33)$$

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Combining Equations (22) and (17) to thereby obtain Equation (34):

$$X_Z = \frac{Z+Z_C}{Z_C}X' = \frac{Z+Z_C}{Z_C} \bullet \frac{Z_C}{Z_{CF}}X_C = \frac{Z+Z_C}{Z_{CF}}X_C \qquad (34)$$

In addition, since Y_Z possesses the same proportional relationship as X_Z, thus

$$Y_Z = \frac{Z+Z_C}{Z_{CF}}Y_C \qquad (35)$$

Therefore, a group of completed equations for calculating the respective X_Z, Y_Z, Z can be finally obtained:

$$Z = -\frac{(\frac{\varphi}{2\pi f} + X_C)D - L_{PF}B}{(\frac{\varphi}{2\pi f} + X_C)C - L_{PF}A}$$

$$X_Z = \frac{Z+Z_C}{Z_{CF}}X_C \qquad (36)$$

$$Y_Z = \frac{Z+Z_C}{Z_{CF}}Y_C$$

Applying the above equations, it is necessary to first operate a height conversion for solving the height distribution. Then perform a position transformation applying the last two equations of the equation group (36) to obtain X_Z and Y_Z. Repeat the above illustrated procedures, an absolute contour of a full fielded 3D surface of the object can be constructed.

Examples

The following examples are provided for the purpose of illustration only and not limitation.

EXAMPLE 1

Referring to Figure 2, there is previously illustrated the imaging device 20, which is

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positioned on the marble table 90.   The first rectilinearly movable axle 40 having a length of 1000 mm with a dust cover is also installed on the platform to align with the optical axis of the imaging device 20.   The first axle 40 which is driven by a hand wheel is made from THK Cooperation, Japan. The object receiving platform 30 is rotatably in 360 degrees affixed

5   to the movable plate which is slidably connected to the axle 40.   An object 80, which is a blade of an aviation engine, is positioned on the platform 30.   The first grating ruler 60 is installed in parallel with the axle 40.   The second rectilinearly movable axle 50 having a length of 400 mm with a dust cover is also installed on the platform to be perpendicular to the first axle 40.   The second axle 50 which is also driven by a hand wheel is made from THK

10   Cooperation, Japan.   The projection device 10 is affixed to a movable plate which is slidably affixed onto the second rectilinearly movable axle 50, where the optical axis of the projection device 10 intersects the second axle 50 at angle γ.   The second grating ruler 70 is installed in parallel with the second axle 50.

15   As further illustrated, the projection device 10 connects to an electricity source 190 through an electrical wire C07.   The measuring camera 21 and imaging camera 28 of the imaging device 20 through the respective cables C08 and C09 are connected to the Matrox Pulser image capture board 100 having four channels, wherein the board 100 is installed in the computer 110.   All the linear positioners are from PI Cooperation, Germany, where the

20   positioner 16 is of the model M224.20 for the projection lens of the projection device, the positioner 17 is of the model M222.20 for the master grating, and the positioner 29A is of the model M224.20 for the movable imaging lens of the imaging device.   They are electrically connected to a direct current motor control board 180 (C-842.40) having four channels through the respective electrical cables C01, C02 and C03, wherein the control board is also

25   installed in the computer 110.

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The projection device 10 is illustrated in Figure 3, comprising the light source 11 which is positioned in front of the condenser 12, the master grating 13 which is positioned in front of the mark point 14 having the cross shape, and the movable projection lens 15. The master grating 13 is movable aligning with an orientation of the grating surface, which

5   movement is controlled by the linear positioner 17. The projection lens 15 is movable aligning with the optical axis of the projection device, whose movement is controlled by the linear positioner 16.

Referring to Figure 4, the imaging device includes an alternative embodiment comprising

10   the measuring light path 120 and imaging light path 130.

The imaging light path 130 includes the movable imaging lens 29, the linear positioner 29A which controls the movement of the movable imaging lens 29, the square prism 24 which is positioned between the image lens 29 and submaster grating 23, the mark point 25

15   which is positioned between the square prism 24 and the reflection mirror 26 which reflects an incident light at 90 degrees, and the imaging camera 28 having a camera lens 27 for recording the imaged mark point 25 having the cross shape.

The measuring optical path 120 includes the movable imaging lens 29, the linear

20   positioner 29A which controls movement of the movable imaging lens 29 aligning with its optical axis, the submaster grating 23, the measuring camera 21 having a camera lens 22 for receiving images of the moire fringes positioned on the submaster grating 23.

During the measurement of the object, first adjust the linear positioner 16 of the

25   projection device 10 to focus the movable projection lens 15, which forms a clear image of the mark point 14 of the cross on the object. Then adjust the linear positioned 29A to focus

the movable imaging lens 29, which forms a clear image on the imaging camera 28 of the

imaging device 20, wherein the image is the imaged mark point of the cross 14 positioned on

the object.   Then through additionally adjusting the second rectilinearly movable axle 50,

make the image of the projected cross 14 on the object surface superpose upon the image of

5   the cross 25 of the imaging device 20.   In this situation, following steps of (2), (3) and (4)

which are illustrated in Figure 7, conduct the automatically focusing, which is to focus the

projection lens through operation of the linear positioned 16, so that the grooves of the master

grating are clearly imaged on the subject surface.   Then through a fine operation of the

linear positioner 29A, make the imaging lens 29 which is finely focused form a clear image

10   on the camera of the imaged grooves which are projected on the object surface.   Under this

condition, conduct operation following steps of (5), (6), (7) and (8) which are illustrated in

Figure 7, wherein the operation includes moving the master grating of the projection device

in the direction which is vertical to the optical axis of the projection device according to a

moved distance of a respective quarter, half and three-quarter grating space, so that a total of

15   four graphs of the moire fringes can be obtained.

Then input the moire fringes recorded on the measuring camera into the image capture

board 100, which results in inputting the digitized moire fringed into the computer 110.

Accordingly, diagrams of the digitized fringes are obtained.   Then apply the phase-shift

20   algorithm to calculate a phase diagram ranging from 0 to 2π.   Finally, reference the zero

phase of the mark point and the equations, calculate the height distribution of one position of

the subject surface, and repeatedly these procedures, obtain X_Z, Y_Z and Z of ever point of the

object surface to thereby acquire accurate contour of the full fielded 3D surface of the object.

It will be appreciated that an accuracy can be $\pm$ 0.01 mm applying the present invention

25   apparatus and method.

EXAMPLE 2

Referring to Figure 2, there is previously illustrated the imaging device 20 (see Figure 9), which is positioned on the marble table 90. The first rectilinearly movable axle 40 having a

5   length of 1000 mm with a dust cover is also installed on the platform to align with the optical axis of the imaging device 20. The first axle 40 which is driven by a hand wheel is made from THK Cooperation, Japan. The object receiving platform 30 is rotatably in 360 degrees affixed to the movable plate which is slidably connected to the axle 40. An object 80, which is a blade of an aviation engine, is positioned on the platform 30. The first grating ruler 60

10   is installed in parallel with the axle 40. The second rectilinearly movable axle 50 having a length of 400 mm with a dust cover is also installed on the platform to be perpendicular to the first axle 40. The second axle 50 which is also driven by a hand wheel is made from THK Cooperation, Japan. The projection device 10 is affixed to a movable plate which is slidably affixed onto the second rectilinearly movable axle 50, where the optical axis of the projection

15   device 10 intersects the second axle 50 at angle γ. The second grating ruler 70 is installed in parallel with the second axle 50.

As further illustrated, the projection device 10 connects to an electricity source 190 through the electrical wire C07. The measuring camera 21 and imaging camera 28 of the

20   imaging device 20 through the respective cables C08 and C09 are connected to the Matrox Pulser image capture board 100 having four channels, wherein the board 100 is installed in the computer 110. All the linear positioners are from PI Cooperation, Germany, where the positioner 16 is of the model M224.20 for the projection lens of the projection device, the positioner 17 is of the model M222.20 for the master grating, and the positioner 29A is of the

25   model M224.20 for the movable imaging lens of the imaging device. They are electrically connected to a direct current motor control board 180 (C-842.400) having four channels from

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PI Cooperation, Germany through the respective electrical cables C01, C02 and C03, wherein the control board is also installed in the computer 110.

The projection device 10 is illustrated in Figure 8, comprising the light source 11, the condenser 12, a round mark point 14, the master grating 13 whose movement is controlled by the grating linear positioner 17, a switcher 18 for switching the mark point and master grating, and the movable projection lens 15 with the linear positioner 16.

The imaging device 20 is illustrated in Figure 9, comprising the measuring camera 21 with the camera lens 22, the switcher 27 for the submaster grating 23 and round mark point 25, and the movable imaging lens 29 with a linear positioner 29A.

During the measurement of the object, first switch the round mark point 13 into the projecting light path. Then adjust the linear positioner 16 of the projection device 10 to focus the movable projection lens 15, which makes a clear image of the round mark point on the object. Then switch the round mark point 25 of the imaging device 20 into the imaging light path. Adjust the linear positioned 29A to focus the movable imaging lens 29 and adjust the length of the second rectilinearly movable axle 50, which makes an image of the projected round mark point 13 on the object surface superpose upon the image of the round mark point 25 of the imaging device 20 on the measuring camera 21. In this situation, perform steps of (2), (3) and (4) which are illustrated in Figure 7, and then conduct automatically focusing, which is, switch the master grating 13 into the projecting light path, and switch the submaster grating 23 into the imaging light path. Under this condition, conduct operation following steps of (5), (6), (7) and (8) which are illustrated in Figure 7, an accurate contour of the full field 3D surface of the object can be obtained with an accuracy of ± 0.01 mm . Additional procedures can be seen in EXAMPLE 1.

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The present invention method and apparatus for measuring contour of the 3D object surface applying the moire fringes includes: applying a method and apparatus of the projected moire interferometry to form graphs of the moire fringes containing information related to a height distribution of surface points of the measured objects; inputting data of light intensities

5   of the optical images which are recorded by the camera into a computer through application of the image capture board; digitizing the graphs of the moire fringes as a pre-data processing of the computation; analyzing a plurality of the moire fringe graphs applying unwrapping algorithm after the graphs have been first treated by the phase shift algorithm; and obtaining phase diagrams containing digitized height information of the measured object surface and

10   values of the X, Y and Z coordinates of every surface point to thereby complete measurement of the absolute contour of the 3D surface, which illustrates a dynamic 3D surface of the measured objects and provides data of the measured surface.

The present invention accomplishes measuring the absolute contour of full fielded 3D

15   surface of objects.   The accuracy is $\pm$ 0.01 mm from the present invention, which are 10-15 folds better, as compared with the currently available commercial instrument.   In addition, the measurement can be completed with 30 seconds applying the present invention method and apparatus.   Therefore, the method and apparatus which possess a high accuracy and speed is particularly useful for measuring objects having sophisticated 3D surface such as the

20   engines.

Of course the present invention is not intended to be restricted to any particular form or arrangement, or any specific embodiment, or any specific use, disclosed herein, since the same may be modified in various particulars or relations without departing from the spirit or

25   scope of the claimed invention hereinabove shown and described of which the apparatus or method shown is intended only for illustration and disclosure of an operative embodiment

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and not to show all of the various forms or modifications in which this invention might be

embodied or operated.

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